Estimation of Urban Evapotranspiration through Vegetation Indices Using WorldView2 Satellite Remote Sensing Images

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ABSTRACT

Irrigation management necessitates better understanding of the water demands of various plants in order to decrease environmental risks and increase water use efficiency. The difficulty in measuring evapotranspiration (ET) from urban landscape plants inhibits the development of sustainable irrigation management strategies. In warm climates, evapotranspiration as the main component of irrigation needs to be quantified accurately. Traditional methods of ET estimation are mostly time-consuming, relatively expensive and lack the coverage required for large areas. Recently, ET estimation has been benefitted from advances in remote sensing (RS) and GIS techniques. Different algorithms and models have been introduced that employ GIS/RS application in order to study various biophysical parameters of vegetation. For instance, the Normalized Difference Vegetation Index (NDVI) is often recommended as a useful indicator to study ET rates. NDVI quantifies the photosynthetic vegetation response to red radiation absorption and near infrared reflectance. This research explores the potential relationship between urban vegetation ET and RS vegetation indices in an urban park; Veale Gardens (VG) within the Adelaide Parklands, Australia. A data set of cloudless WorldView2 imageries of consecutive seasons in 2012 were used to quantify NDVI and NDRE values. ERDAS IMAGINE was employed to image processing, geo-referencing, atmospheric correction and NDVI and NDRE map generation. NDVI and NDRE maps were clipped to the borders of VG and then imported to ArcGIS for zonal statistical analysis. ET rate for VG was estimated using an observational-based approach, namely Water Use Classifications of Landscape Species (WUCOLS). A short description of the WUCLOS method is provided, which is then applied to the study area. In-situ weather and vegetation data were collected and irrigation monitoring data were provided by the local water authority. A panel of horticulturists assessed and rated the most common plant species in the park in terms of drought tolerance. The relationship between RS-based NDVI and ET_{WUCOLS} was investigated. Results showed a strong positive correlation (R^2 = 0.95, P < 0.01) between ET of urban landscape vegetation and NDVI. The outcomes indicate that remotely sensed NDVI may be an efficient indicator of the water demand of urban landscape vegetation. In contrast, NDRE is not a suitable indicator of urban vegetation water demand.

Keywords: Evapotranspiration, remote sensing, landscape coefficient, NDVI. NDRE, WUCOLS, Australia

1. INTRODUCTION

Remote Sensing (RS) and Geographical Information Sciences (GIS) are helpful tools for site specific studies of vegetation monitoring and interpretation. Relatively recently, the spatial resolution of RS images were dramatically improved from hundreds of meters to the sub-meter level and the temporal resolution has also greatly improved (Mulla, in-press).

Different algorithms and models have been introduced employing GIS/RS applications to study many biophysical parameters of vegetation. Mathematical combinations of different bands, several combinations of spectral bands, and a variety of spectral reflectance has resulted in developing different vegetation indices. Although, numerous vegetation indices have been developed, most of these are based on the separation of vegetation from other environmental phenomena like soil and water. In another words, RS-based vegetation indices measure vegetation greenness optically through vegetation cover, leaf chlorophyll content, leaf area, etc. Applications of vegetation indices differ from leaf to global scales (Vina et al., 2011) driven from a variety of satellites including MODIS, Landsat, ASTER, SPOT5, QuickBird, IKONOS, GeoEye, WorldView1, WorldView2, etc. with different spatial, spectral, temporal and radiometric resolutions. For instance, the most popular vegetation index of NDVI relies on the principle concept of a relationship between absorption of visible light and resilient reflectance of near-infrared light to the chlorophyll in green materials of vegetation (Vina et al., 2011). NDRE measures leaf chlorophyll concentration that can estimate vegetation healthiness. NDVI is more sensitive to canopy cover while NDRE is based on the chlorophyll red-edge wavelengths (Eitel et al., 2010; Eitel et al., 2011).

Nouri et al. (2012) reviewed the relationship between agricultural and non-agricultural vegetation indices and evapotranspiration (ET). They recommended vegetation indices particularly NDVI as a useful indicator to study vegetation characteristics and consequently evapotranspiration rates. Statistical analysis and ground measurements have confirmed that a near linear relationship can be found between vegetation indices and photosynthesis by vegetation canopy (Glenn et al., 2008). Long-term RS data analysis by Rossato et al. (2005) showed that evapotranspiration and NDVI are have a near-linear relationship. A linear relationship between NDVI and basal crop coefficient for irrigated agricultural fields was reported by Duchemin et al. (2006).

In this research, we investigate the temporal variation of RS-based NDVI and NDRE, and urban landscape evapotranspiration and the relationship of NDVI-ET and NDRE-ET. A plant factor in the Water Use Classifications of Landscape Species (WUCOLS) was estimated through field monitoring and in-situ weather data acquisition. Costello and Jones (1994) introduced a practical approach, known as the Water Use Classifications of Landscape Species (WUCOLS) to achieve optimum plant growth. WUCOLS is based on the approach used in crop water requirement estimation (FAO-24 and FAO-56) and this takes into account a landscape coefficient, consisting of a species factor, a density factor and a micro-climate factor. An expert committee listed different plant species in varying categories of water demands that relate to their landscape coefficients. These were empirically assigned based on field evaluation (Costello and Jones, 1994; Costello et al., 2000). Density and micro-climate factors are also evaluated through field observation.

2. METHODS AND MATHERIALS

2.1. Study area

The study was conducted in an urban park namely Veale Gardens within the Adelaide Parklands, South Australia, Australia. Veale Gardens with an area of 9.6 hectares is located between latitudes of 34.9357 and 34.9376 E and longitudes of 138.5945 and 138.6002 S (Fig. 1). The area is semi-arid with a mean annual rainfall of 549 mm and 1600 mm of pan evaporation per annum (BOM, 2010). The park contains more than 60 different species, size, and type of landscape trees and shrubs and a broad coverage of Kikuyu turf grass irrigated by a sprinkler system. The research was undertaken from March to August 2012.

Fig.1 Veale Gardens in the Adelaide Parklands

2.2. Image processing

WorldView2 images covering Veale Gardens on 18th March, 29th June and 17th August 2012 were obtained from DigitalGlobe WorldView2, which is a high spatial and spectral resolution satellite that provides 8 spectral sensors in the visible to near-infrared range. Having accurate boundaries is important in the precise determination of each pixel land cover (Johnson and Belitz, 2012). The main reasons for selecting WorldView2 were: large-scale capacity of 975,000 km^2 per day; average revisit of 1.1 days; 46cm panchromatic and 184 cm 8-band multispectral spatial resolution with swath

width of 16.4 km at nadir. The range of eight bands varies from 400-450 nm (band 1 - coastal blue), 450-510 nm (band 2 - Blue), 510-580 nm (band 3 - Green), 585-625 nm (band 4 - Yellow), 630-690 nm (band 5- Red), 705-745 nm (band 6 - Red-Edge), 770-895 nm (band 7- NIR1), to 860-1040 nm (band 8 - NIR2). The images were orthorectified and geometrically corrected.
For most satellites, NDVI is computed from satellite image reflectance data of the red and near-infrared bands:

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}}$$

where ρ_{NIR} is the reflectance of the near-infrared wavelength band and ρ_{red} is the reflectance of the red wavelength band. The NDVI values range from 1- to 1 with zero or negative values for non-vegetated areas and water bodies and values greater than 0.5 for healthy vegetation (Johnson and Belitz, 2012).

Frequent and reliable high resolution access to the spectral band of Red-Edge data enables WorldView2 images to improve the accuracy and sensitivity of vegetation studies (DigitalGlobe, 2009; Zhou et al., 2012). The images were checked for orthorectification, but the orthorectification process resulted in barely any accuracy change in the image, which is probably because of the flatness of the terrain in the study area. Then the area of interest was extracted from the image. Due to the physical relationship of radiance to surface properties, atmospheric components need to be removed. The widely-used ATCOR family of software using MODTRAN calculations was employed for atmospheric correction (Richter and Schlapfer, 2002; Schläpfer and Richter, 2002; Brazile et al., 2008). For WorldView2, NDRE is computed from satellite image reflectance data of the red-edge and near-infrared bands:

$$NDRE = \frac{\rho_{NIR} - \rho_{red-edge}}{\rho_{NIR} + \rho_{red-edge}}$$

2.3 Field data

A landscape plant coefficient was applied to the reference evapotranspiration to calculate the urban landscape evapotranspiration. An observational-based approach known as the Water Use Classification of Landscape Plants (WUCOLS) was employed to quantify the urban vegetation characteristics (Costello and Jones, 1994; Costello et al., 2000; Salvador et al., 2011; Nouri et al., 2012). A list of the most common plant species was compiled and irrigation water delivery data were provided by the local water authority. The reference evapotranspiration data was obtained from quality controlled Bureau of Meteorology (BOM) data; the nearest station being at Kent Town (KT), which is located on the east side of the city, 2.92km from Veale Gardens. Kent Town (Station 023090) data were downloaded from the BOM website (http://www.bom.gov.au/climate/data/). The principles of the WUCOLS approach were followed and landscape evapotranspiration rates were determined.

3. RESULTS AND DISCUSSION

The geospatial boundary of Veale Gardens was hand digitized using a panchromatic image and field observations (Fig 2). If the center of a pixel fell within the study area, it was taken belong to it.

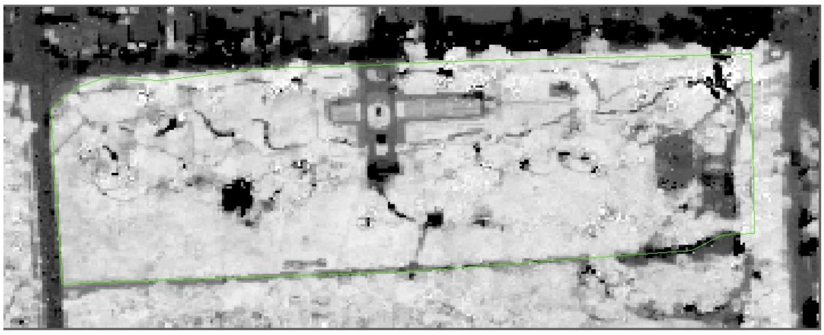

Fig 2. Borders of Veale Gardens in an NDVI image

NDVI and NDRE were defined. NDVI is the combination of NIR1 and Red bands and NDRE is the combination of NIR and Red-edge bands. The zonal statistics of NDVI and NDRE for Veale Gardens are listed in Table 1.

Table 1. Zonal statistics of NDVI and NDRE

Month	Mean NDVI	STD	Mean NDRE	STD
March	0.691	0.356	0.384	0.256
June	0.523	0.41	0.552	0.214
Aug	0.612	0.334	0.361	0.203

In order to assign an urban landscape evapotranspiration coefficient, K_L, for Veale Gardens, three factors of species, density and microclimate were estimated. A list of vegetation species and their water demand based on WUCOLS principles showed that the most common vegetation fall within a low to moderate range of water needs. Hence a species factor of 0.53 was selected. A density factor of 1 was allocated to Veale Gardens corresponding to the canopy cover. Considering the minor influence of surrounding urban features including parking lots, streets, buildings and a glass house in Veale Gardens, a microclimate factor of 1.05 was selected for the whole park. The final urban landscape evapotranspiration coefficient (K_L) of 0.56 was calculated as the product of the species, density and micro-climate factors. The results are summarized in Table 2.

Table 2. Estimated landscape evapotranspiration during the study period

Date	Mar-12	Apr-12	May-12	Jun-12	Jul-12	Aug-12
ET_0	140.6	91.7	54.2	43.5	47.1	64.2
ET_L-WUCOLS	78.736	51.352	30.352	24.36	26.376	35.952

Temporal variations of NDVI, NDRE, and ET_L from March to August 2012 are presented in Fig 3.

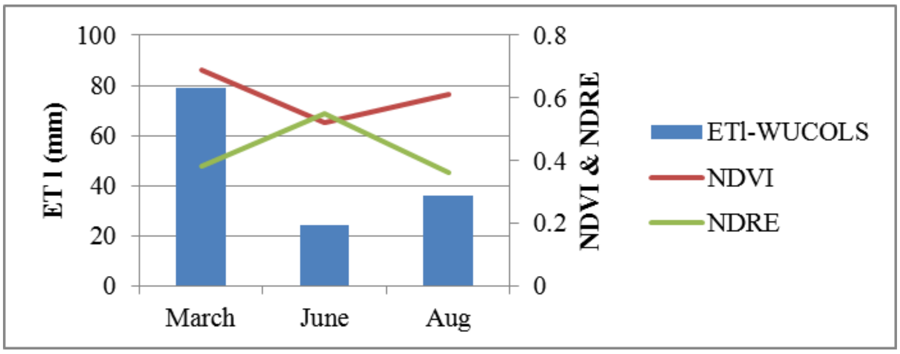

Fig 3. Temporal variation of NDVI, NDRE and ET

Data analysis showed a strong correlation between the WorldView2 normalized difference vegetation index and urban landscape evapotranspiration (R= 0.937) in contrast to a lack of correlation between WorldView2 normalized difference red-edge index and urban landscape evapotranspiration (R= -0.578). The relationships of NDVI to ET_L and NDRE to ET_L during March to August 2012 are shown in Fig 4.

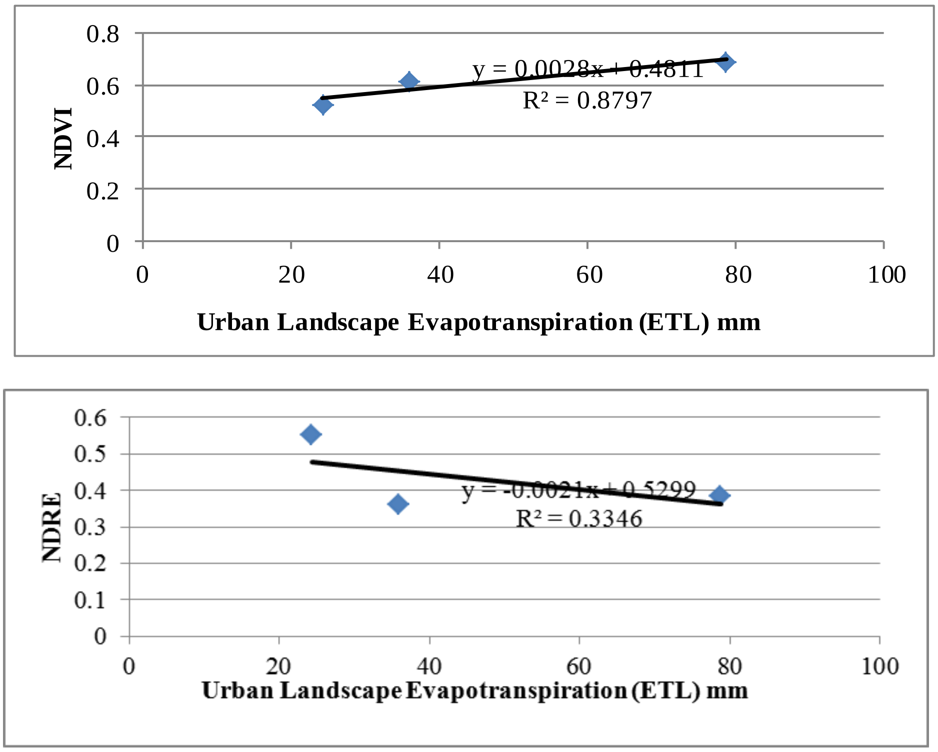

Fig 4. NDVI-ET and NDRE-ET relationships

4. CONCLUSION

These results show that NDVI obtained from WorldView2 images is a good indicator of evapotranspiration of urban landscape vegetation for Veale Gardens. However, a longer study period would help to improve accuracy. This finding is in line with several studies that have found a strong and reliable relationship between aerial-satellite-based NDVI measurements and ground-based ET measurements (Glenn et al., 2012; Rossato et al., 2005; Nagler et al., 2007; Palmer et al., 2009; Devitt et al., 2010; Johnson and Belitz, 2012; Nagler et al., 2012). All Australian states, including South Australia, have weather station networks that provide daily reference evapotranspiration for important urban green spaces and agricultural sites. By accounting for field conditions, this RS method can provide simple, quick and low-cost urban vegetation water requirement estimates compared to more costly field-based approaches. The spatial and temporal variation of heterogeneous mixed urban landscape vegetation areas requires an approach with a higher spatial resolution and an improved capability for frequent updating. The method described in this paper is not only simple and rapid, but also has the capability of observing the heterogeneity of vegetation through Hyperspectral images.

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C0068

H. Nouri. "Estimation of Urban Evapotranspiration through Vegetation Indices Using WorldView2 Satellite Remote Sensing Images". EFITA-WCCA-CIGR Conference "Sustainable Agriculture through ICT Innovation", Turin, Italy, 24-27 June 2013.